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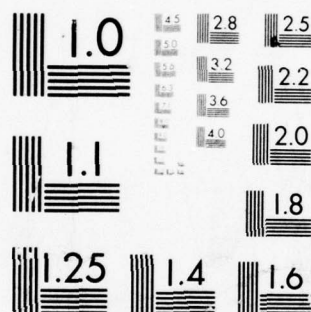
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# THE CUTTING OF ICE WITH WATER JETS

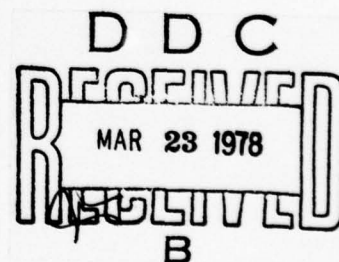
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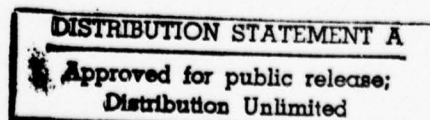
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MECHANICAL ENGINEERING

REPORT  
MD-54

NRC NO. 16416



6 THE CUTTING OF ICE WITH WATER JETS,

COUPE DE LA GLACE PAR JETS D'EAU

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11 Nov 77

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# SUMMARY

A new portable, self-contained facility for investigating the cutting of ice with water jets has been built and tested. Following the initial trials some modifications and improvements to the facility have been recommended.

From current and previous ice cutting tests it has been established that significant cuts in ice can be made over a wide range of conditions. At moderate pressures, that is less than 2,000 psig, and low traverse speeds, it has been possible to cut through ice 28 inches thick. Correlation with previous test results by regression analysis has been made.

# RÉSUMÉ

On a construit et mis à l'essai une nouvelle installation portative et indépendant pour étudier la coupe de la glace par des jets d'eau. Après les premiers essais, on a recommandé d'y apporter certaines modifications et améliorations.

Les résultats des derniers essais et des essais antérieurs sur la coupe de la glace ont révélé qu'il est possible de réaliser des coupes dans une grande gamme de conditions. À des pressions moyennes, c'est-à-dire inférieures à 2,000 l./po<sup>2</sup>, et à des vitesses de coupe peu élevées, on a réussi à couper une épaisseur de glace de 28 pouces. On a ensuite établi, par analyse de régression, une corrélation entre ces résultats et ceux d'essais antérieurs.

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## THE CUTTING OF ICE WITH WATER JETS

### 1.0 INTRODUCTION

Canada's present ice breaking capability is limited to Class 4 with the 27,000 hp Louis St. Laurent<sup>(1)</sup>. A new ice breaker currently proposed by the Canadian Coast Guard would have a Class 7 capability with 90,000 hp. Also it has been suggested that a 150,000 hp Class 10 polar ice breaker be designed and built with the ability to go anywhere in the Arctic at any time of the year.

Because of the enormous power required for conventional ice breaking, there is an incentive to find some more efficient way of breaking ice. One approach, with a potential to reduce significantly the vessel propulsion power requirements, would be to weaken the ice sheet and/or create stress concentrations in it by cutting a groove (or grooves) through the upper surface of the ice. A relatively simple device utilizing a water jet as the cutting tool may be capable of cutting suitable grooves. Such a device has the potential for development into a rugged, practical system for notching ice ahead of the ice breaker's bow.

Previous work of this Division's Gas Dynamics Laboratory in cutting a variety of materials with high pressure water jets led to exploratory small scale ice cutting trials in the laboratory<sup>(2)</sup>. While these trials showed that ice could indeed be cut with high pressure water jets, extrapolation of the results to a full scale system was impractical. In collaboration with the US Army's Cold Regions Research and Engineering Laboratory, various series of cuts were made in ice ranging from floating ice<sup>(3)</sup> to manufactured ice<sup>(4)</sup> to lock wall ice collars<sup>(5)</sup> with a pumping system about one full order of magnitude larger than the laboratory system. These cuts covered a fairly wide range of conditions, from relatively high speed shallow penetration cuts to low speed relatively deep penetration cuts. Extrapolating about two orders of magnitude from these results, while not at all reliable, did indicate that a realistic full scale system might be possible.

To further explore the cutting of ice with water jets, a new moderate pressure portable facility has been built co-operatively by the Low Temperature and Gas Dynamics Laboratories. This report describes the new facility and the results of the initial series of tests.

### 2.0 NEW ICE CUTTING FACILITY

This facility basically consists of a diesel engine driven main pumping system installed in an ISO 20' x 8' x 8' container, a gasoline spark ignition engine driven self-priming feed pump system mounted on a utility trailer and a water jet cutting lance with support column for mounting on a traversing device. Except for the need of a traversing device, the entire facility is self-contained once it is placed in position. See also Appendix A for additional details.

#### 2.1 Main Pumping System

The main pump is an eight-stage, 4" x 4" x 10" centrifugal pump with horizontally split casing. It is capable of producing about 2,300 psig at up to about 400 US gpm. The performance curves are given in Figure 1.

A water cooled 1191 C.I.D. V-8 diesel engine with aftercooled turbo-chargers drives the main pump. The "Hydra-Mechanical" governor is set to limit the full load speed to 2,000 rpm and the low idle speed to 500 rpm. The engine is rated at 480 bhp @ 1,800 rpm for continuous duty, 610 bhp @ 2,000 rpm for intermittent duty and 735 bhp @ 2,000 rpm maximum. For the engine performance curves see Figure 2.

To match pump and engine speeds an available speed increaser with a 2.2 to 1 ratio is interposed between the engine and the pump. This speed increaser has ample capacity, 5,000 hp @ 3,600 rpm.

A centrifugal clutch coupling with a high idle speed of 560 rpm connects the engine to the speed increaser, thus allowing the engine to be started without load and the pump to be stopped without stopping the engine. It is rated at 840 hp @ 1,800 rpm.

The pump is coupled to the speed increaser through an oil filled high speed gear coupling.

In Figure 3 the limitations on pump performance imposed by the rated capabilities of the diesel engine have been superimposed on the pump performance curves, assuming no slip of the centrifugal clutch.

All components of the main pumping system, with the exception of the engine silencer and batteries, are mounted on a tubular steel base designed to maintain alignment of the engine, speed increaser and pump under the worst expected conditions of support. This entire system is enclosed in a 20' X 8' X 8' ISO group IC container, and is bolted to the container floor (consequently, the container should not be subjected to accelerations or decelerations beyond about 2 G's). Both the batteries and the silencer are fastened directly to the container.

The water piping system within the container is shown in Figure 4. To prevent freezing of water in the system after shutdown, drain connections are provided to permit rapid draining of the entire system with the exception of small quantities in the bottom of five of the eight pump volutes. After draining, any water left in the system is diluted with methanol fed into the system at critical points from a drum seated in a cradle on the container roof. A propane space heater provides back-up protection as well as allowing for a "warm" start-up of the system.

## 2.2 Feed Pump System

A 4" X 4" self-priming centrifugal pump can be used to supply water at low pressure from a reservoir (usually beneath the ice sheet) to the main pumping system for both engine cooling and feed to the main pump. It is capable of pumping about 400 US gpm @ 80 psig when running at 2,600 rpm and can pass spherical solids as large as 3/4" diameter.

An air cooled 108 C.I.D. V-4 gasoline fuelled spark ignition engine drives the feed pump. At the governed speed of 2,600 rpm the engine is rated at 29 hp.

A manually controlled power take-off clutch, integral with the engine, and a serpentine steel band flexible coupling connect the pump to the engine. Thus the engine can be started and warmed up without load and the pump can be stopped without shutting down the engine.

## 2.3 Cutting Lance and Support Column

A convergent stainless steel nozzle mounted on the end of the lance accelerates the water to create a high velocity water jet capable of cutting ice. The mounting accommodates interchangeable nozzles and allows for the insertion of various flow modification devices into the flow immediately upstream of the nozzle. The lance, a stainless steel pipe approximately 4 ft. long, provides a straight channel of about 26 pipe diameters without discontinuity for the stabilization of the flow to the nozzle.

For the first series of tests the swing of a hydraulic crane with a telescoping boom was used to traverse the cutting lance. A relatively lightweight triangular latticed column was mounted from the head of the crane boom using existing fittings on the head. The mounting was designed to avoid the application of twisting moments to the crane boom, to provide for vertical adjustment of the column, and to allow use of the main crane hook. By locating the adjustable lance mounting at the centroid of the column, eccentric loading due to jet reaction was minimized. Overall adjustment allowed the nozzle tip to be positioned from 12'-6" to 19'-3" below the upper mounting point. For the first series of tests this adjustment was set to provide a dimension of 16'-0" for this distance.

A 12-ft. length of 2" diameter pipe, connected to the lance inlet, extended upwards through the open centre of the column for the first test series. A 90° elbow at the top of the pipe permitted a simple and convenient connection to the supply line.

## 2.4 Water System

The entire water system is shown diagrammatically in Figure 4. Water is drawn through the suction strainer and one or two 20-ft. lengths of 4" diameter heavy duty suction hose by the feed pump. This pump supplies the water to the container system through one or two 50-ft. lengths of 4" diameter heavy duty discharge hose. When more water is needed for engine cooling than for ice cutting, the excess is returned to the reservoir through the return line, consisting of the remaining length(s) of discharge hose (a total of three lengths of discharge hose are available). All low pressure hose connections are made with mating quick-connect fittings, thereby allowing a variety of hose arrangements.

As the water enters the container it passes through a fine strainer (3/16" diameter holes). A small quantity is passed through a filter (10 micron) for cooling and sealing the pump. The remainder can be directed through a variety of paths, depending on the setting of the butterfly valve and the three-way cock.

(a) Butterfly closed, cock straight through

All the flow will pass through the engine heat exchangers and return to the reservoir.

(b) Butterfly closed, cock connecting heat exchanger return to pump inlet

All the flow will pass in series through the engine heat exchangers and main pump discharging through the cutting nozzle.

(c) Butterfly open, cock straight through

The flow will split as per the extent of the butterfly valve opening. That portion passing through the engine heat exchangers will return to the reservoir while the remainder will pass through the main pump and discharge from the cutting nozzle.

(d) Butterfly open, cock connecting heat exchanger return to pump inlet

The flow will split as per the extent of the butterfly valve opening. That portion passing through the engine heat exchangers will re-mix with the remainder of the flow at the pump suction. The total flow will then pass through the main pump and discharge from the cutting nozzle.

On leaving the container the water flows to the cutting lance through two lengths of 2" diameter high pressure hose totalling 75 ft. in length. Pipe is used to provide any additional length necessary.

Two 24' lengths of 1-1/4" diameter plastic drainage hose are available to carry drain water and/or blowdown from the fine strainer away from the container.

Water pressure can be measured at the inlet and outlet of both the feed pump and the main pump, and at the ice cutting nozzle.

## 3.0 ICE CUTTING TEST SITE

A spring-fed pond adjacent to Building U-89 at Uplands was selected as a convenient test site (Fig. 5). This site had adequate accessibility, adequate size (about 300 ft. X 100 ft.) and adequate depth (up to about 8 ft.). By late January, it had an 18-inch natural ice cover with only a light covering of snow.



Because of a desire for a thicker layer of ice, snow was removed from a 100-ft. radius circular segment of the pond. This area was then flooded by pumping water onto the ice surface from beneath the ice sheet. Flooding continued daily, weather permitting, over a five-week period from 28 January to 4 March, 1977. The total ice thickness at the end of this period reached 28 to 30 inches.

#### 4.0 ICE CUTTING TEST SET-UP (FIG. 6)

On 8 March 1977, the container complete with the main pumping system was placed and levelled on the bank of the pond immediately adjacent to the site selected for the crane. The trailer with the feed pump system was placed on the ice surface nearby. On the following day the crane was positioned and "levelled" on the selected site (the levellest and most accessible available). The cutting lance support column was mounted on the head of the crane boom and the cutting lance and pipe were mounted in the column.

One length of high pressure hose with one 20-ft. length of pipe was laid on and hung from the partially extended crane boom. The remaining length of high pressure hose was then draped between the crane boom and the main pump connection in the container. As the crane boom was swung through the maximum arc to be used in the tests the extension of the crane boom was adjusted to the maximum allowed by the high pressure line.

The low pressure suction and return hoses were placed in holes drilled at convenient locations through the ice. Both lengths of suction hose were used for the suction line while one length of discharge hose connected the feed pump to the main pumping system. The remaining two lengths of discharge hose were used for the return line.

To provide a reference for the traverse speed measurement, ten posts (see foreground Fig. 6) were set at 10 ft. increments on a 90-ft. radius arc centred on the swing axis of the crane.

#### 5.0 ICE CUTTING TEST PROCEDURES

Prior to the ice cutting test the feed pump engine was started and warmed up. When it was running smoothly, the clutch was engaged to start the feed pump which required some assistance to establish its prime. Circulation was established through the heat exchangers for diesel engine cooling and through the seal and cooling systems of the main pump. All the heat exchanger water was returned to the pond. The diesel engine was then started and run at slow idle to warm up. Since the cuts were to be made with the crane swinging from east to west, the crane was swung to the east end of the pond in readiness for the first test.

With the proper nozzle installed on the lance and the crane boom elevation adjusted to establish the desired nozzle stand-off distance, low pressure water was re-directed through the main pump and out the cutting nozzle in order to prime the pump and purge air from the high pressure lines. The feed pump was then accelerated to full power and the diesel engine to the desired pump operating condition. Once the high velocity water jet was stabilized the crane boom was swung to traverse the jet at the desired speed, thereby cutting a continuous groove in the ice.

While traversing, the following data was recorded:

- (a) engine rpm
- (b) main pump discharge pressure
- (c) nozzle pressure
- (d) nozzle stand-off distance
- (e) time to traverse the arc subtended by a pair of posts

(f) cine and still photographs.

At the end of the desired cut the swing of the boom was stopped, the diesel engine was returned to low idle and the feed pump was slowed to a reduced load condition. Afterwards the depth of cut and radius at which it was made were measured and recorded.

Prior to the next cut any changes of stand-off distance, nozzle size, and/or radius of traverse were made. For nozzle changes the low pressure water to the nozzle was cut off, being re-directed through the return line to the pond. Subsequent cuts either continued on the same arc or started a new arc after the radius was adjusted.

Upon completion of each day's testing the water system was drained and charged with sufficient methanol to dilute any remaining water.

## 6.0 ICE CUTTING TESTS

Fourteen ice cutting tests were attempted as shown in Table I. However, Test No. 1 was aborted before starting the traverse, since the centrifugal clutch slipped badly and became overheated. Therefore, for Test No. 2 the smallest nozzle, 0.375" diameter, was tried so that the power demand of the pump would be reduced. Tests No. 2 through 14 were successfully completed, although the centrifugal clutch had to be water cooled during Tests No. 13 and 14.

### 6.1 Tests No. 2 Through 5 Summary

Nozzle diameter	0.375" (smallest)
Nozzle pressure	1,640 to 1,910 psig
Nozzle flow	170 to 183 US gpm
Hydraulic power	162 to 204 hp
Nozzle stand-off	6 to 36 inches
Traverse speed	9 to 36 fpm
Engine power	Maximum available for all but Test No. 2.

For all these tests the minimum depth of cut was 18", that is, approximately to the upper surface of the bottom clear layer of ice (see Section 7). At the slower traverse speeds complete penetration was achieved in some areas.

### 6.2 Tests No. 6 Through 10 Summary

Nozzle diameter	0.500"
Nozzle pressure	1,490 to 1,560 psig
Nozzle flow	288 to 294 US gpm
Hydraulic power	250 to 268 hp
Nozzle stand-off	12 to 60 inches
Traverse speed	10 to 52 fpm
Engine power	maximum available

Penetration was complete for all but the fastest traverse.

### 6.3 Test No. 11 Summary

Nozzle diameter	0.500" (flow straightener installed immediately upstream of nozzle)
Nozzle pressure	1,530 psig

Nozzle flow	292 US gpm
Hydraulic power	260 hp
Nozzle stand-off	48 inches
Traverse speed	18 fpm
Engine power	maximum available

Cut was 21" deep, that is, into but not through the bottom clear layer of ice.

#### 6.4 Test No. 12 Summary

Nozzle diameter	0.500" (flow straightener installed immediately upstream of nozzle)
Nozzle pressure	1,560 psig
Nozzle flow	294 US gpm
Hydraulic power	268 hp
Nozzle stand-off	48 inches (approx.)
Traverse speed	not measured
Engine power	maximum available

After manually drilling an eight-inch diameter hole through the ice with an ice auger to get an accurate ice thickness measurement, a block approximately 4 ft. square surrounding the hole was cut out with the water jet. The block is shown in profile in Figure 7 and from the underside in Figure 8.

#### 6.5 Tests No. 13 and 14 Summary

Nozzle diameter	0.656" (largest)
Nozzle pressure	1,050 psig
Nozzle flow	416 US gpm
Hydraulic power	255 hp
Nozzle stand-off	48 inches
Traverse speed	17 to 160 fpm
Engine power	maximum available

Penetration was complete for the slow speed traverse and 8" to 12" for the high speed traverse. The centrifugal clutch was slipping badly for both of these tests.

Figure 9 shows the pump performance curves with both the engine characteristics and the theoretical nozzle performance curves superimposed. The operating points for Tests No. 2 through 14 are also indicated.

#### 7.0 ICE QUALITY

On the day following the water jet ice cutting tests, sample blocks of ice were cut from near the centre of the pond for subsequent strength testing. These blocks were transported to the Low Temperature Laboratory where they were stored in a cold chamber at  $-10^{\circ}\text{C}$ .

As can be seen from Figure 7, which shows a cross-section of the pond ice, many different layers of ice were discernible. Except for the top surface ice, which was badly canded, three distinctly different grades of ice were identifiable. At the bottom of the ice sheet was a single layer of clear ice approximately 11" thick. On top of this were three or four apparently similar layers of semi-opaque ice containing many included air bubbles. The total thickness of semi-opaque ice was about 7". The top 10" of ice apparently consisted of many thin layers of opaque "white" ice containing a great deal of air.



During the week following the ice cutting tests the blocks were cut into more than 30 individual test specimens, several from each of the three distinct grades of ice. Each specimen was tested for strength and a representative number were tested for density<sup>(6)</sup>. Except for brief periods, during which the samples were transferred between cold chambers, they were maintained at  $-10^{\circ}\text{C}$ .

The clear bottom layer of ice was typical of clear fresh water ice in both strength and density. However, the laminated semi-opaque ice had only 75% of the strength and 95% of the density of the bottom ice, while the top opaque "white" ice had only 60% of the strength and 85% of the density of the bottom ice.

The laminated semi-opaque layers in the centre of the ice sheet apparently were the result of successive submergences of the ice sheet and precipitation; the clear bottom layer appears to have grown on the bottom of the initial ice sheet and the top opaque "white" ice layer was the result of the daily flooding of the surface.

## 8.0 ANALYSIS OF TEST DATA

Since the ice thickness was limited to only 28", many cuts penetrated through the entire sheet of ice. This left only seven tests with any measurable depth of cut and only five with a measurable maximum. In addition, only the final cut, Test No. 14, differed appreciably from the others. Consequently, the data from these tests alone were not adequate for analysis.

The inferior strength of the top layers of ice also raised a concern as to the relationship between the results of these tests and the cutting of more normal ice. However, it was also suspected that the energy dissipation characteristics of this aerated ice were greater than for more normal ice. Since these two characteristics would somewhat compensate for each other, it was decided to compare the results with data accumulated from previous testing.

Exploratory analysis indicated that the results from the early laboratory trials<sup>(2)</sup> were inconsistent with the rest of the results. Apparently, the low power, high pressure operating regime involved in these trials was so totally different from the operating conditions of the remaining tests that they had an inordinate effect on the overall results. Therefore, they were excluded from further analysis.

Table II lists, along with the results from the current test series, the results from the previous testing, with the exception of the inconsistent laboratory results. Data sets No. 1 through 9 list the results of cuts made in a sheet of floating ice<sup>(3)</sup>; data sets No. 10 through 19 list the results of cuts made in manufactured ice<sup>(4)</sup>; data sets No. 20 through 30 list the results of cuts made in lock wall ice collars<sup>(5)</sup>; and data sets No. 31 through 42 list the results of the current series of cuts made in a sheet of floating ice. Note that the last five data sets, No. 38 through 42, involve cuts through the ice sheet and, therefore, may not represent the true penetration potential for these conditions; unless otherwise stated they were not included in the regression analysis which follows.

### 8.1 Preliminary Regression Analysis

Of the various parameters which may have an effect on the depth of cut, those that were selected for measurement and analysis were nozzle traverse speed, nozzle diameter, nozzle pressure and nozzle stand-off distance.

Expressed mathematically,

$$Y = f(u, d, p, s) \quad (1)$$

where: Y = depth of cut (inches)  
u = nozzle traverse speed (fpm)  
d = nozzle diameter (inches)  
p = nozzle pressure (psig)  
s = nozzle stand-off distance (inches).

As a first approximation it was assumed that a zero value for this function would result in a zero depth of cut. Therefore, multiple linear regression analysis was applied to a logarithmic transformation of this expression, so that,

$$\log Y = A + B \log u + C \log d + D \log p + E \log s \quad (2)$$

By taking the anti-logarithms of this expression, the resulting function was of the form,

$$Y = A \times u^B \times d^C \times p^D \times s^E \quad (3)$$

Thus this function yielded a set of exponents for the parameters. In addition, analysis of variance indicated highly significant correlation with nozzle traverse speed, nozzle diameter and nozzle pressure, but no significant correlation with nozzle stand-off distance. A repeat log-log MLR with the nozzle stand-off distance non-dimensionalized by dividing it by the nozzle diameter did not improve the correlation. Thus, the log-log MLR analysis was repeated without the nozzle stand-off distance parameter. This resulted in the following relationship:

$$Y = 0.00044 \frac{d^{2.48} \times p^{1.94}}{u^{0.56}} \quad (4)$$

It was noted that the numerator of this equation was not too dissimilar to the expression for power in a fluid jet,

$$P = C \times d^2 \times p^{3/2} \quad (5)$$

where: P = hydraulic power (hp)  
C = dimensional constant  
d = nozzle diameter (inches)  
p = nozzle pressure (psig)

A third log-log MLR analysis was run with the nozzle diameter and nozzle pressure parameters replaced with a single parameter, the calculated theoretical hydraulic power in the jet. The resulting relationship was,

$$Y = 0.26 \frac{p^{1.10}}{u^{0.55}} \quad (6)$$

## 8.2 Final Regression Analysis

Since Equation (6) was so close to the more rational relationship,

$$Y = f\left(\frac{P}{\sqrt{u}}\right) \quad (7)$$

a linear regression analysis of this form was applied to the data without the log-log transformations. This yielded,

$$Y = -1.0 + 0.43 \frac{P}{\sqrt{u}} \quad (8)$$

Statistically this equation was significant beyond the 99.9% level. In addition, 95% of the data fell between the following limits,

$$Y_{+2\sigma} = 2.7 + 0.51 \frac{P}{\sqrt{u}} \quad (9)$$

$$Y_{-2\sigma} = -4.7 + 0.35 \frac{P}{\sqrt{u}} \quad (10)$$

When the linear regression was repeated with the five data sets involving through cuts, No's. 38 through 42, included, the relationship was only slightly changed to,

$$Y = -0.04 + 0.41 \frac{P}{\sqrt{u}} \quad (11)$$

The differences between Equations (11) and (8) were those to be expected from the under-estimation of cutting depth for the five data sets.

A similar linear regression analysis that had been performed previously<sup>(4)</sup> on the first 19 data sets of Table II had yielded the relationship,

$$Y = -2.2 + 0.45 \frac{P}{\sqrt{u}} \quad (12)$$

Comparison of Equations (12) and (8) indicated little change in the relationship between power, traverse speed and depth of cut with the additional data used to obtain Equation (8).

## 9.0 OBSERVATIONS AND DISCUSSION

### 9.1 New Ice Cutting Facility

For all tests utilizing the 21/32" diameter nozzle (Tests No. 1, 13 and 14) the centrifugal clutch failed to lock-up. It continued to slip about 200 rpm over the duration of Tests No. 13 and 14. No such slip occurred when the smaller nozzles were in use.

Subsequent investigation has revealed that the power required to supply a 21/32" diameter nozzle follows closely the clutch rated capacity curve. While clutch lock-up may be obtainable when using this large a nozzle under ideal operating conditions, it is unlikely that it will be achieved in the more rigorous real operating environment. More realistically, the actual capacity of this clutch can be expected to impose an upper limit on nozzle diameter somewhat smaller than 21/32". A nozzle of 9/16" diameter should be within the capabilities of the clutch, it would provide a significant extension of the operating range beyond that provided by the 1/2" diameter nozzle, and it would permit operation with almost the greatest net power input to the jet that this facility can deliver. Should significant additional clutch capacity be available when operating with a 9/16" diameter nozzle, it could be enlarged until the maximum clutch capacity is approached.

During commissioning of the engine, water was unavailable for pump loading when the engine governor controls were being set. Consequently, the settings were made only under high and low idle conditions. The resulting engine performance was limited to less than the intermittent duty rating of the engine (see Fig. 9). The governor controls will be readjusted under load to maximize the engine power output.



To assist in operation of the facility, additional instrumentation is needed, a tachometer to measure actual pump speed and a thermocouple readout to monitor continuously the diesel engine exhaust stack temperature. The thermocouple readout will allow maximum power to be drawn from the engine without over-temperature damage to the turbo-chargers.

## 9.2 Ice Cutting Tests

This series of tests has shown that significant cuts can be made in ice with water jets produced with nozzle pressures as low as 1,050 psig. However, due to the laminated ice structure (Fig. 7) with the relatively weak upper layers, the ice cutting characteristics of the water jets used in these tests may not be representative of their characteristics in more normal ice. Specifically,

- (a) a threshold pressure higher than 1,050 psig may be necessary to cut more typical fresh water ice,
- (b) the energy dissipation characteristics of the opaque "white" ice may have been greater than for more typical ice,
- (c) the bond of the clear bottom ice layer to the remainder of the ice sheet was apparently weak.

The latter condition is particularly apparent upon examination of Figures 7 and 8. In Figure 7 it can be readily seen that the water jet has cut cleanly through all but the bottom clear ice layer. Figure 8 shows that significant delamination has occurred between the bottom clear ice and the first opaque ice layer. In addition, Figure 11 illustrates a phenomenon often found during these tests; the jet was causing the delamination, which then allowed part of the water jet to escape through the resulting gap and up the neighbouring slot cut during a previous pass. This may explain why portions of many of the cuts apparently terminated at or near the top surface of the bottom clear ice layer. However, Table I indicates that this layer was penetrated by the water jet during Tests No. 2, 3, 10 and 11.

Figures 7 and 8 also illustrate one manner in which full penetration was achieved. While the upper layers were cut cleanly, entire sections of the bottom clear layer were apparently broken out. Since the fractures were at approximately  $45^\circ$  to the plane of the ice sheet, and since they were often remote from the water jet cut, it is postulated that the delaminated clear bottom layer failed by exceeding the principal shear strength of the ice where the bending stresses were highest, i.e. generally at the ends of a beam with fixed ends.

Figures 12 and 13 show the water jets cutting ice during Tests No. 9 and 13 respectively while Figure 14 shows the high speed traverse of Test No. 14. Figure 15 shows the cut made during Test No. 3. From Figures 11, 14 and 15 it can be seen that fairly large ice particles were ejected from the slot during the cutting. The considerable amount of dirt on the ice surface, most apparent in Figures 7 and 14, was deposited there when the penetrating water jet disturbed the bottom of the pond. Towards the end of Test No. 12 the jet so disrupted the bottom that weeds blocked the intake strainer.

## 9.3 Nozzle Performance

All nozzles produced quite coherent jets, with the jets from the  $3/8''$  diameter nozzle and the  $1/2''$  diameter nozzle (Fig. 12) having the greatest and similar coherence. The  $1/2''$  diameter nozzle with the flow straightener insert immediately upstream of the nozzle produced a noticeably inferior jet; its ice cutting ability was also noticeably inferior to that of the plain  $1/2''$  diameter nozzle. The  $21/32''$  diameter nozzle (Fig. 13) produced what appeared to be the least coherent jet but it cut just as well as the smaller plain nozzles. Microscopic examination revealed small flaws in the metal at the exit of the  $3/8''$  diameter nozzle and a slightly rounded exit on the  $1/2''$  diameter nozzle. However, the  $21/32''$  diameter nozzle had an exit close to the sharp corner ideal. An objective method of measuring jet coherence would assist in assessing the quality of jet produced by nozzles of different design and workmanship. An alternative would be the measurement of stagnation pressure and/or impingement force at varying stand-off distances.



#### 9.4 Traversing System

While the hydraulic crane did provide a safe and convenient means for traversing the nozzle without deadweight loading of the ice sheet, it did not provide adequate control of either nozzle traverse speed or nozzle stand-off distance. For several tests considerable variations in traverse speed were measured during the test runs. The cine photographs also revealed a rather jerky, pause-and-continue motion to the traverse. This may account for some of the variation in depth of cut.

Because of the flexibility of the crane boom and an inability to truly level the crane, the nozzle stand-off distance varied both as the nozzle pressure changed and as the crane was swung through the traversing arc.

For any traversing system it would be desirable to continue use of the latticed column with the long straight approach pipe to the nozzle. This would optimize the approach flow conditions, thus providing the most coherent water jet and, therefore, the most intense concentration of energy on the point of jet impingement.

#### 9.5 Ice Cutting with Water Jets

While the present series of tests could not in themselves define the ice cutting abilities of water jets, comparison with previous ice cutting tests indicated compatibility at least. Although there was considerable scatter in the data, particularly at the greater penetrations (Fig. 10), the regression analysis indicated excellent correlation.

The measurement of penetration or depth of cut, while providing a range, did not yield a good statistically useful measurement. Much of the scatter mentioned above must have originated with this data. For each test a series of careful measurements at fixed intervals should be made.

Extrapolation of Equation 8 to realistic ice breaking requirements, while rather extreme, does yield the interesting estimate that about 5,000 hydraulic horsepower (at the nozzle) would be needed for full penetration under Class 10 polar ice breaking conditions of 10-ft. penetration at 3 knots. At the 95% confidence limits, Equations 9 and 10 indicate that between about 4,000 hhp and about 6,200 hhp would be the range of power required for such Class 10 service. On this basis the present facility should have an ultimate capacity of a little more than one order of magnitude smaller than a practical system for use with polar ice breakers.

### 10.0 CONCLUSIONS AND RECOMMENDATIONS

#### 10.1 New Ice Cutting Facility

A new self-contained portable facility for cutting ice with water jets has been built and tested. It will ultimately be capable of producing water jets at pressures as high as 2,300 psig with flow rates exceeding 250 US gpm. At reduced pressures, about 1,500 psig, flow rates greater than 400 US gpm will be possible.

While the centrifugal clutch in the high pressure pump drive presently limits the range of the system, the rather small unavailable high flow, low pressure regime may have little relevance to ice cutting. It is recommended that the rather wide range of available conditions be fully explored before attempting to extend the range. In this connection, a 9/16" diameter nozzle and a 7/16" diameter nozzle should be made. The former would be useful in defining the limits of clutch capacity and testing the high flow, low pressure regime; the latter would allow operation very close to the conditions corresponding to the maximum engine power. If, after exploring the available range of operating conditions, it is still desirable to explore the unavailable regime, the present clutch should be modified to increase its capacity and the operating procedures should be altered to suit. A set of the necessary components should be obtained so that clutch modification can be readily accomplished.

Readjustment of the engine governor control to allow full exploitation of the engine should be done at the first opportunity.

A tachometer should be obtained for monitoring the actual pump speed and for developing the best operating procedures to obtain the maximum clutch performance. A continuous thermocouple readout should be obtained for monitoring the engine exhaust stack temperature, so that the engine may be exploited to its fullest.

A superior traversing system with better control of traverse speed and stand-off is needed. Traverse speed should be controllable from about 3 fpm to 300 fpm. While there is no need to reproduce accurately any particular speed, the actual absolute speed should be readily measurable and it should remain constant throughout each test run. Stand-off should be variable from about 3 inches to 60 inches, again with the proviso that it be constant and measurable during each test run.

## 10.2 Ice Cutting with Water Jets

Thirteen successful cuts were made in ice with various water jets in this test series. While cuts were made with nozzle pressures as low as 1,050 psig, the ice that was cut at this pressure was weaker than typical fresh water ice because of considerable air inclusion. At some places an apparently weak bond, between the bottom clear ice layer and the semi-opaque ice layer immediately above it, was broken by the jet with the result that parts of the bottom clear layer broke off in large chunks when the traverse speed was slow. At other places the clear ice was cut by the water jet.

When compared with previous ice cutting tests the present cuts conformed to the general characteristics. Regression analysis indicated an excellent overall correlation. However, measurements of penetration should be taken more carefully and at specific intervals to provide a statistically more useful measurement.

While the ice cutting tests to date correlate penetration with power and traverse speed, the separate effects of the individual components of power, pressure and flow rate, should be determined. Since from a cost and maintenance standpoint it would be desirable to operate at the lowest pressure that will produce the desired results, it will be necessary to determine what threshold pressure is necessary to cut ice and if a higher pressure, per se, is beneficial.

Exploration of the operating regime available with this facility should be fully explored next winter at a convenient location with a maximum thickness of natural floating ice. However, for those conditions when the penetration exceeds this ice thickness, it is recommended that an artificial ice slab of appropriate size and thickness be built at a convenient location on land. With such a slab, the limits of jet penetration could be explored.

Factors other than those considered to date should be included in future testing. Nozzle and approach piping design and workmanship should be examined; the effect of angling the jet in the direction of traverse should be examined, and measurements of the ice quality should be taken.

Possibly a measurement of the jet coherence, stagnation pressure or impingement force with respect to distance from the nozzle would provide an objective measure of jet quality which ultimately could be related to the nozzle and piping characteristics.

At present an impact test involving the impact of a weighted sphere onto an ice surface is felt to provide the best available measure of ice quality as it relates to water jet cutting.

## 11.0 REFERENCES

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Martin, R.A.



TABLE I  
ICE CUTTING WITH WATER JETS

Test No.	Engine Speed (rpm)	Pump Speed (rpm)	Nozzle Dia. (inches)	Nozzle Press. (psig)	Nozzle Flow (US gpm)	Hydraulic Power (hp)	Avg. Traverse Speed (fpm)	Nozzle Stand-off (inches)	Depth of Cut (inches)		Remarks
									Min.	Max.	
1	--	--	0.656	--	--	--	--	--	--	--	Clutch overheated, test aborted
2	1700	3740	0.375	1640	170	162	36	12	18	22	
3	1780	3916	0.375	1910	183	204	14.0	12	18	26	
4	1780	3916	0.375	1820	180	190	10.5	6	18	through	
5	1780	3916	0.375	1820	180	190	13.3	36	18	through	
6	1670	3674	0.500	1560	294	268	11.3	60	through	--	
7	1640	3608	0.500	1490	288	250	12.6	12	through	--	
8	1650	3630	0.500	1550	294	265	10.8	39	through	--	
9	1650	3630	0.500	1530	292	260	38	60	through	--	
10	1650	3630	0.500	1530	292	260	44	50	16	28	
11	1670	3674	0.500	1530	292	260	18.0	48	21	21	
12	1670	3674	0.500	1560	294	268	--	48	through	--	
13	1680	3220*	0.656	1050	416	255	17.4	48	through	--	
14	1650	3220*	0.656	1050	416	255	120	48	8	12	

With flow straightener

With flow straightener, cutting out block

Clutch slipping  
\*Pump speed from pump Curve

TABLE II  
ICE CUTTING WITH WATER JETS  
REGRESSION PARAMETERS

Data Set	Min. Depth of Cut Y(inches)	Avg. Traverse Speed u(fpm)	Nozzle Dia. d(inches)	Nozzle Pressure p(psig)	Nozzle Stand-off s(inches)	Hydraulic Power P(hp)	Remarks
1	2.24	320	0.089	9,300	3	124	Cuts made in floating ice sheet <sub>(3)</sub>
2	2.60	242	0.089	9,500	3	128	
3	3.15	159	0.089	9,500	3	128	
4	3.27	148	0.089	9,700	3	132	
5	5.90	58	0.089	9,800	3	134	
6	8.00	40	0.089	9,800	3	134	
7	5.90	34	0.063	11,700	3	87	
8	8.50	32	0.089	10,000	3	138	
9	8.74	13.5	0.063	11,000	3	80	
10	9	16	0.086	9,600	1.5	121	Cuts made in manufactured ice <sub>(4)</sub>
11	8	16	0.086	9,600	2.5	121	
12	12	12	0.086	8,500	5	101	
13	13.5	9	0.086	9,600	4	121	
14	28	3	0.086	9,100	5	112	
15	28	3	0.086	9,400	2	117	
16	12	3	0.152	3,000	2	66	
17	22	3	0.063	12,000	3	91	
18	34	3	0.086	9,500	2	129	
19	29	3	0.086	9,400	4	117	
20	16	15	0.093	8,500	3	118	Cuts made in lock wall ice collars <sub>(5)</sub>
21	15	13.3	0.093	9,000	6	128	
22	20	9.6	0.093	9,000	6	128	
23	20	8.6	0.093	8,500	3	118	
24	12	8.6	0.093	8,500	22	118	
25	32	4.4	0.093	8,500	3	118	
26	36	3.6	0.093	8,500	3	118	
27	10	3	0.152	3,000	3	66	
28	18	3	0.101	7,000	3	104	
29	42	3	0.093	8,500	3	118	
30	20	2.3	0.093	8,500	32	118	
31	8	120	0.656	1,050	48	255	Cuts made in floating ice sheet
32	16	44	0.500	1,530	50	260	
33	18	36	0.375	1,640	12	162	
34	21	18	0.500	1,530	48	260	
35	18	14	0.375	1,910	12	204	
36	18	13.3	0.375	1,820	36	190	
37	18	10.5	0.375	1,820	6	190	
38	28	38	0.500	1,530	60	260	Cuts made through floating ice sheet
39	28	17.4	0.656	1,050	48	255	
40	28	12.6	0.500	1,490	12	250	
41	28	11.3	0.500	1,560	60	268	
42	28	10.8	0.500	1,550	39	265	

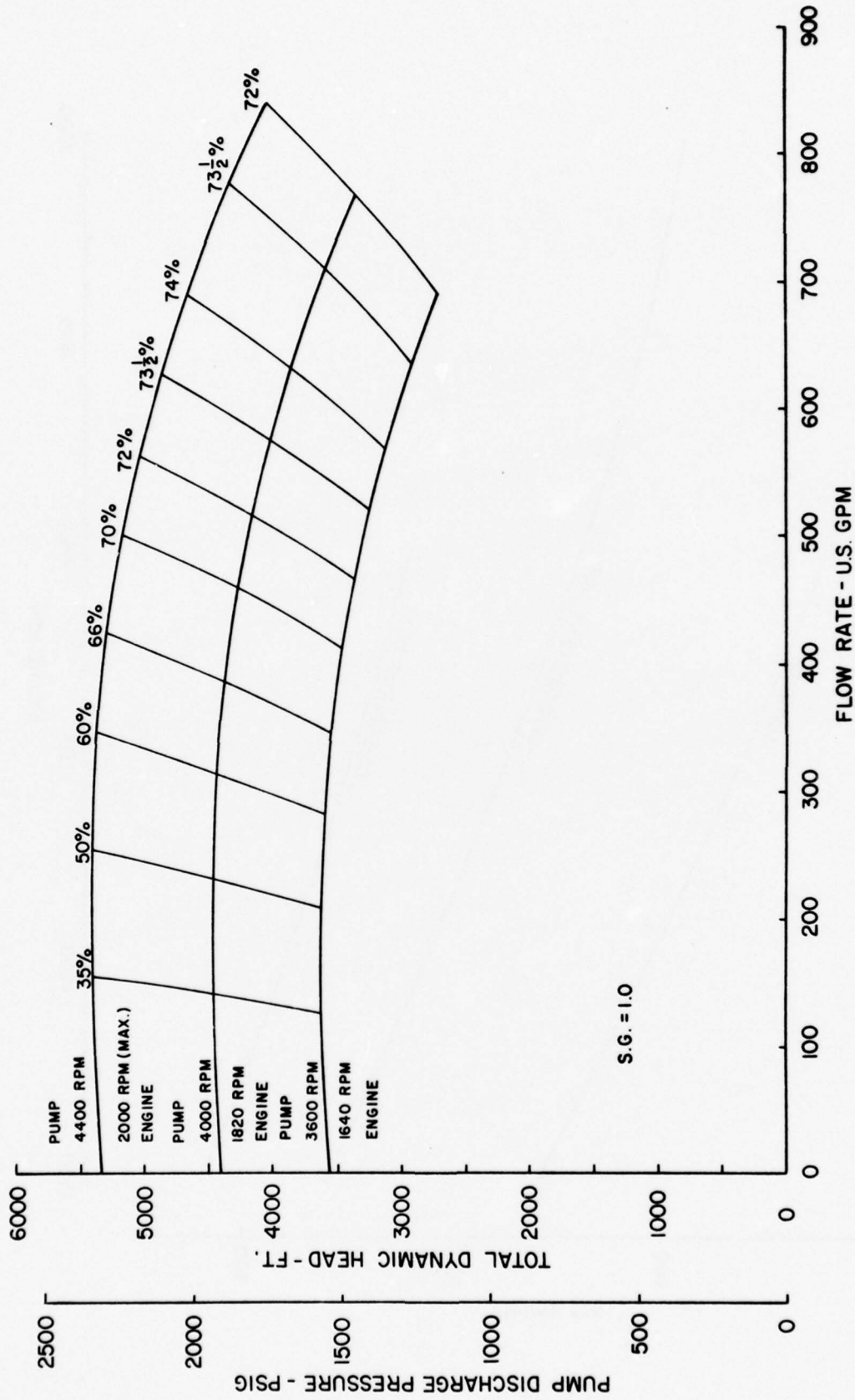


FIG. 1: PUMP PERFORMANCE CURVES

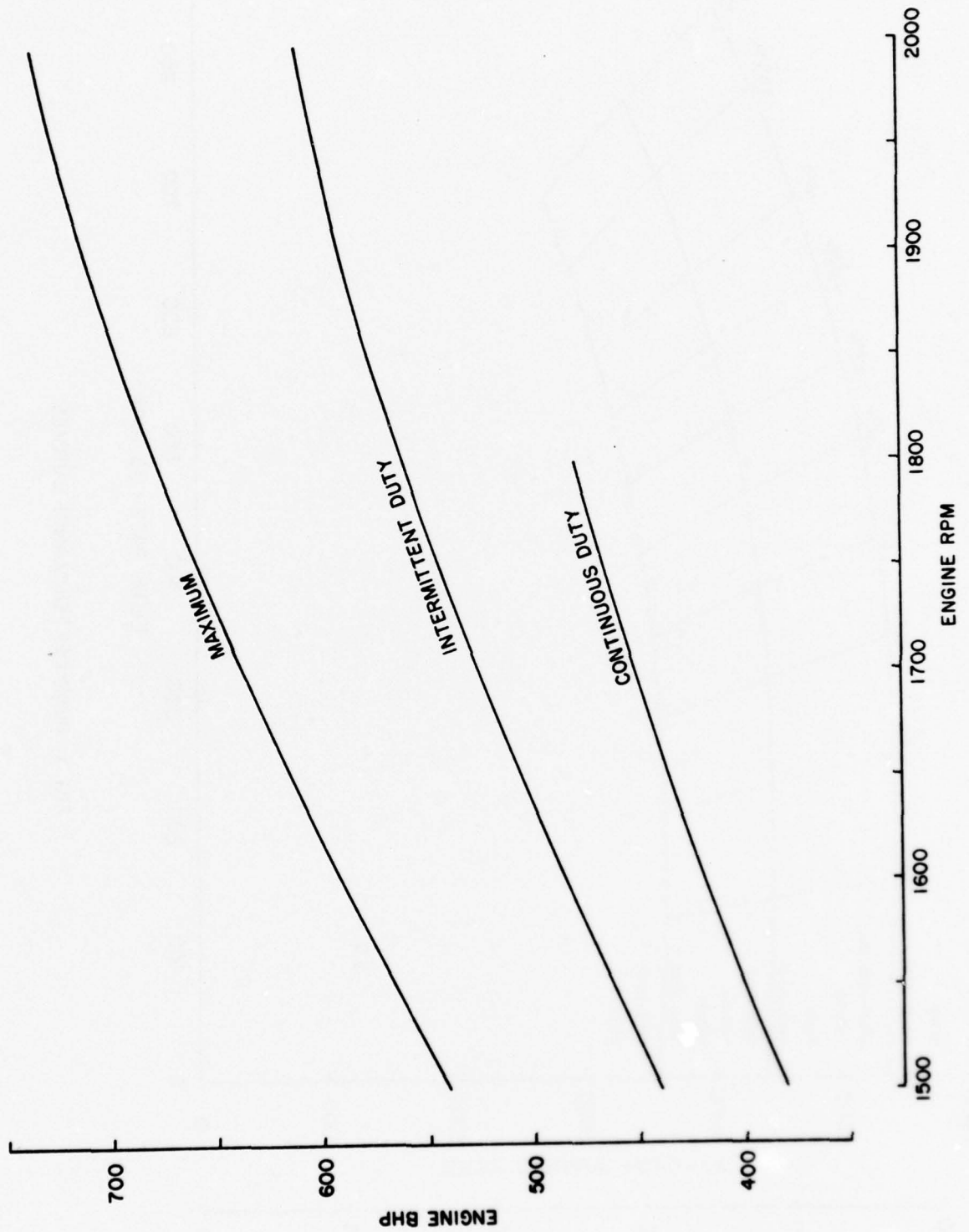


FIG. 2: DIESEL ENGINE PERFORMANCE CURVES



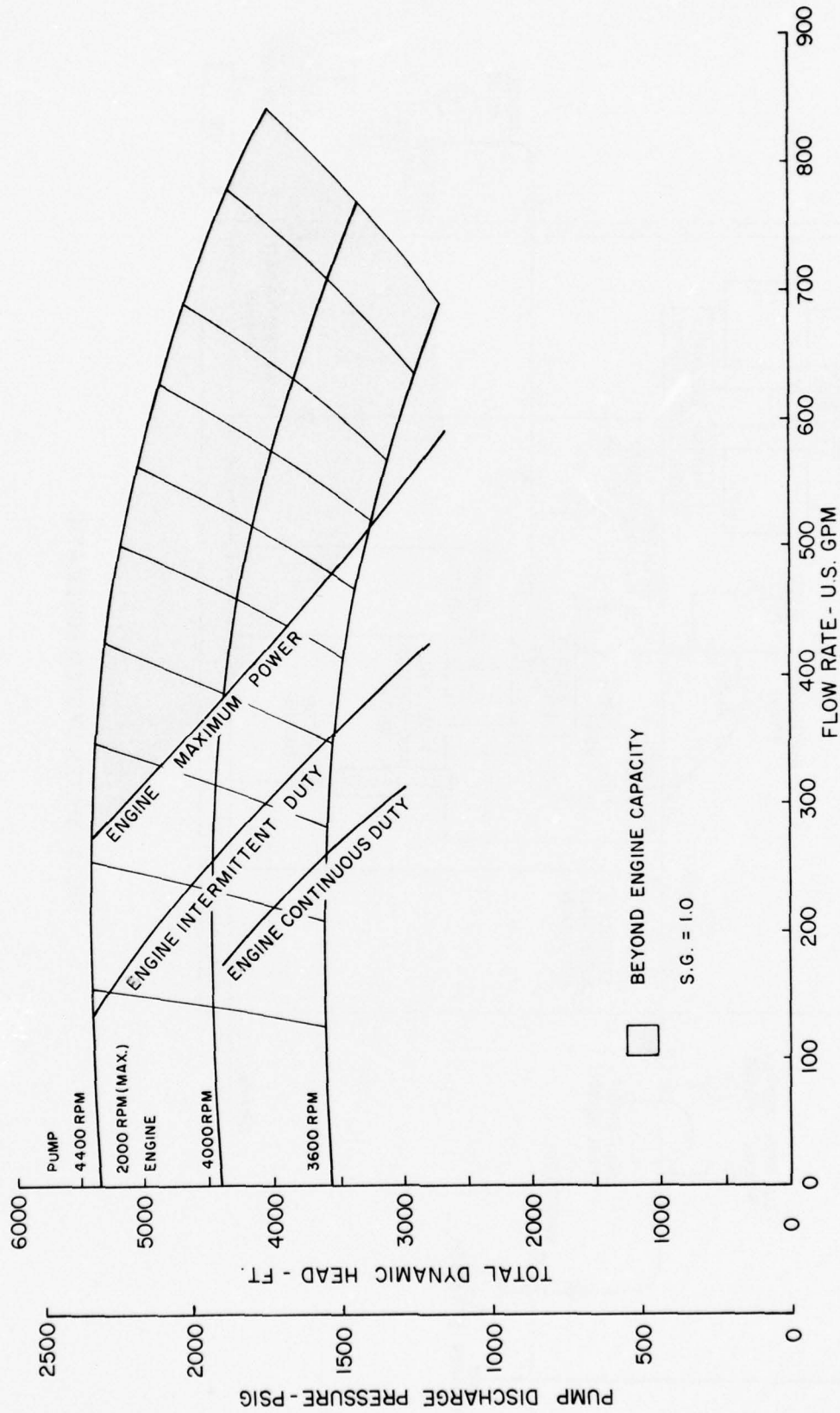


FIG. 3: LIMITATIONS ON PUMP PERFORMANCE IMPOSED BY DIESEL ENGINE

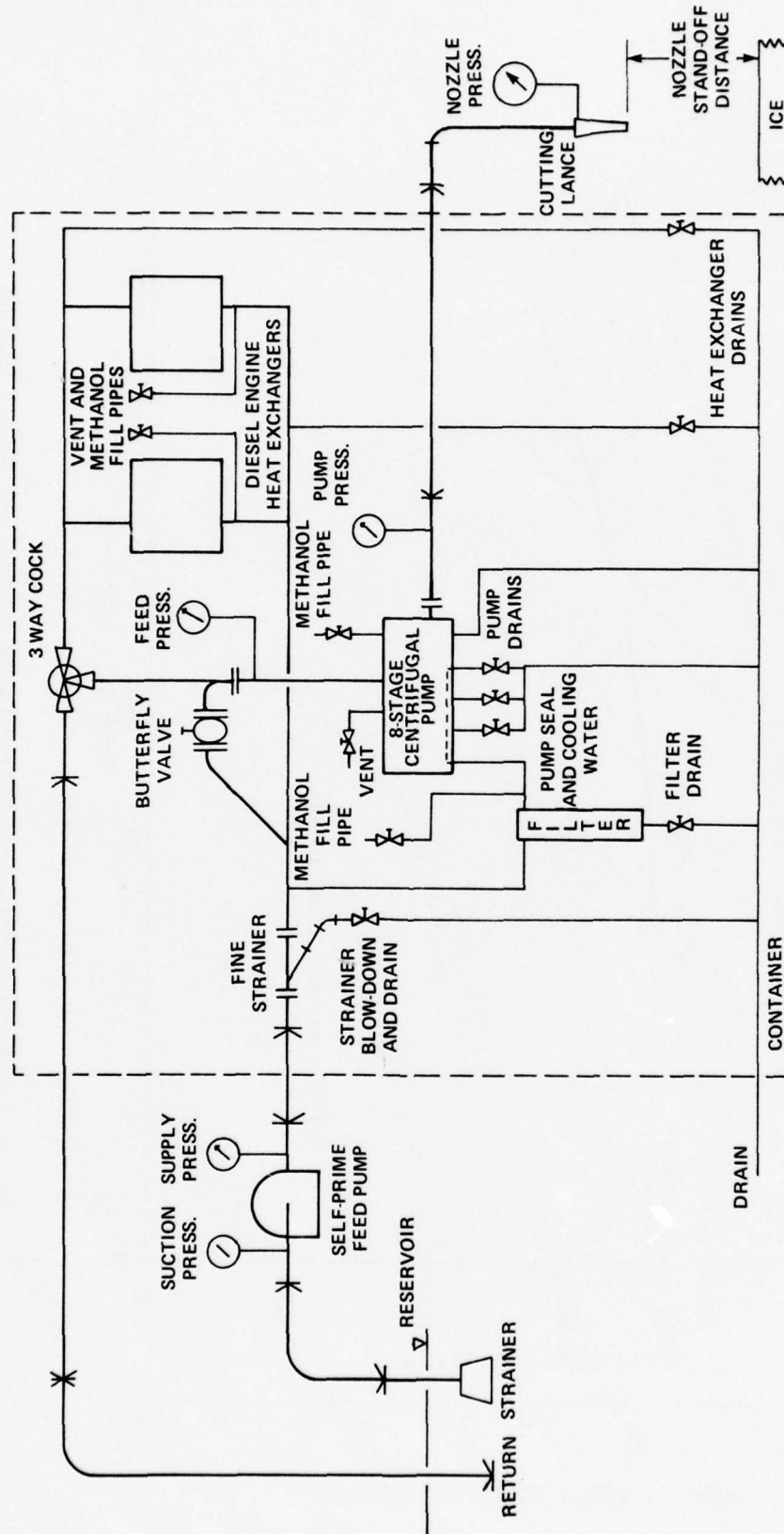


FIG. 4: WATER SYSTEM SCHEMATIC



FIG. 5: ICE CUTTING TEST SITE

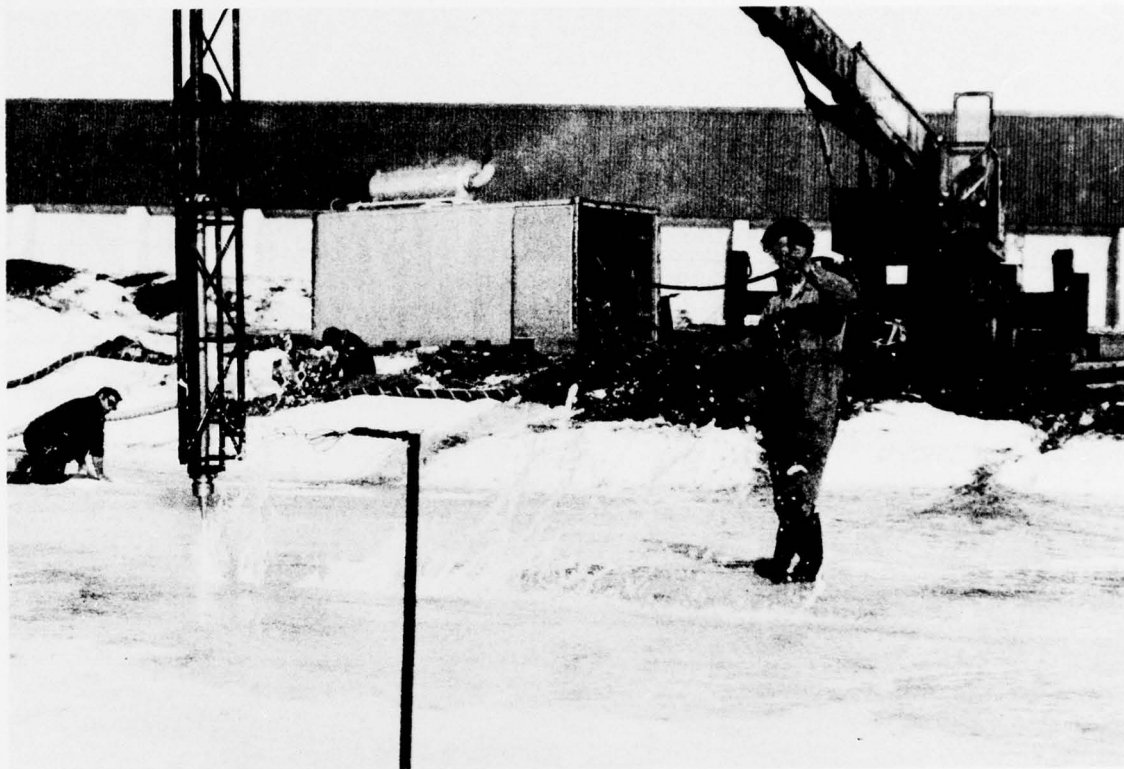


FIG. 6: ICE CUTTING TEST SET-UP



FIG. 7: CROSS-SECTION OF POND ICE





FIG. 8: BLOCK CUT FROM POND WITH WATER JET

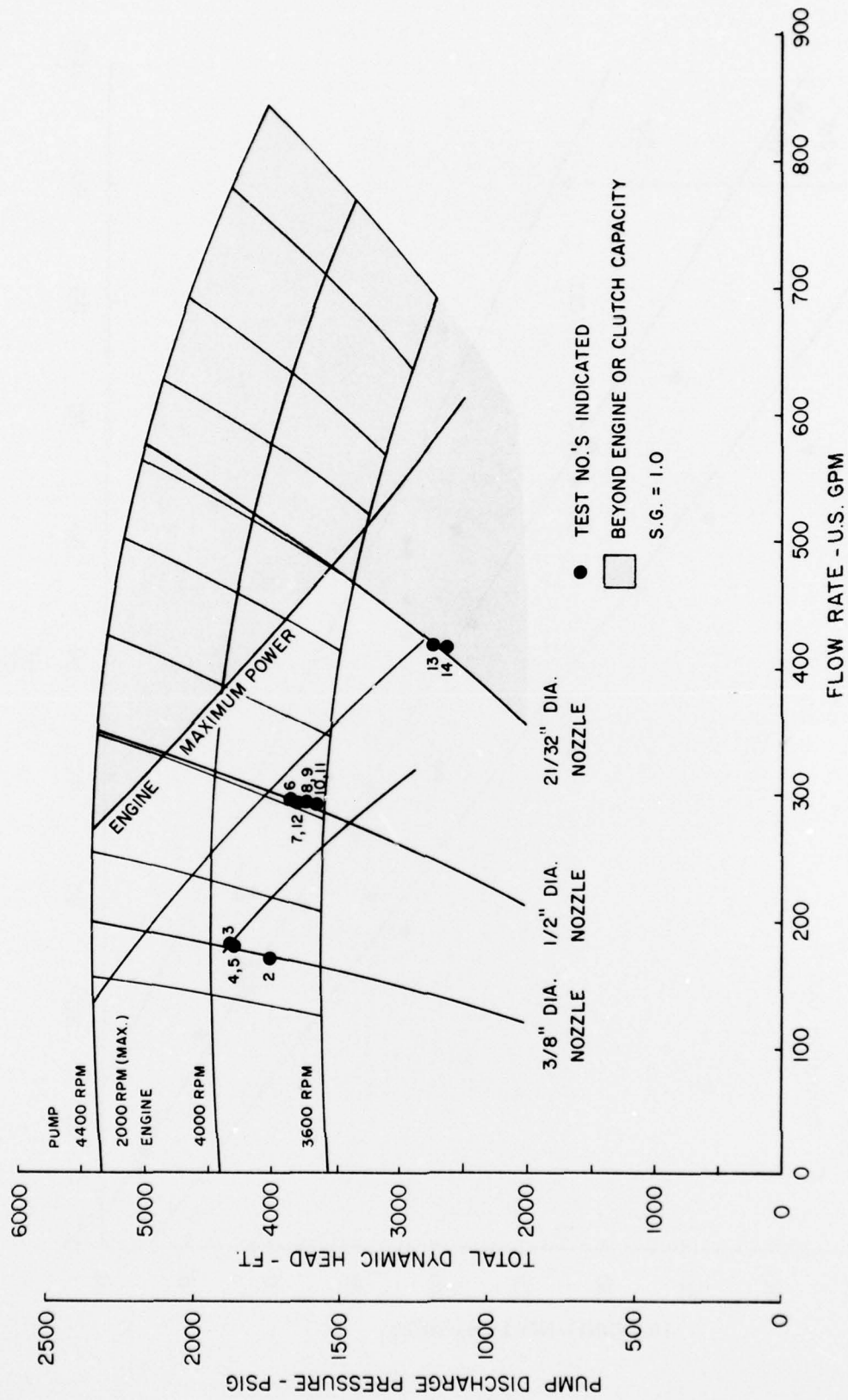


FIG. 9: ICE CUTTING TEST OPERATING CONDITIONS



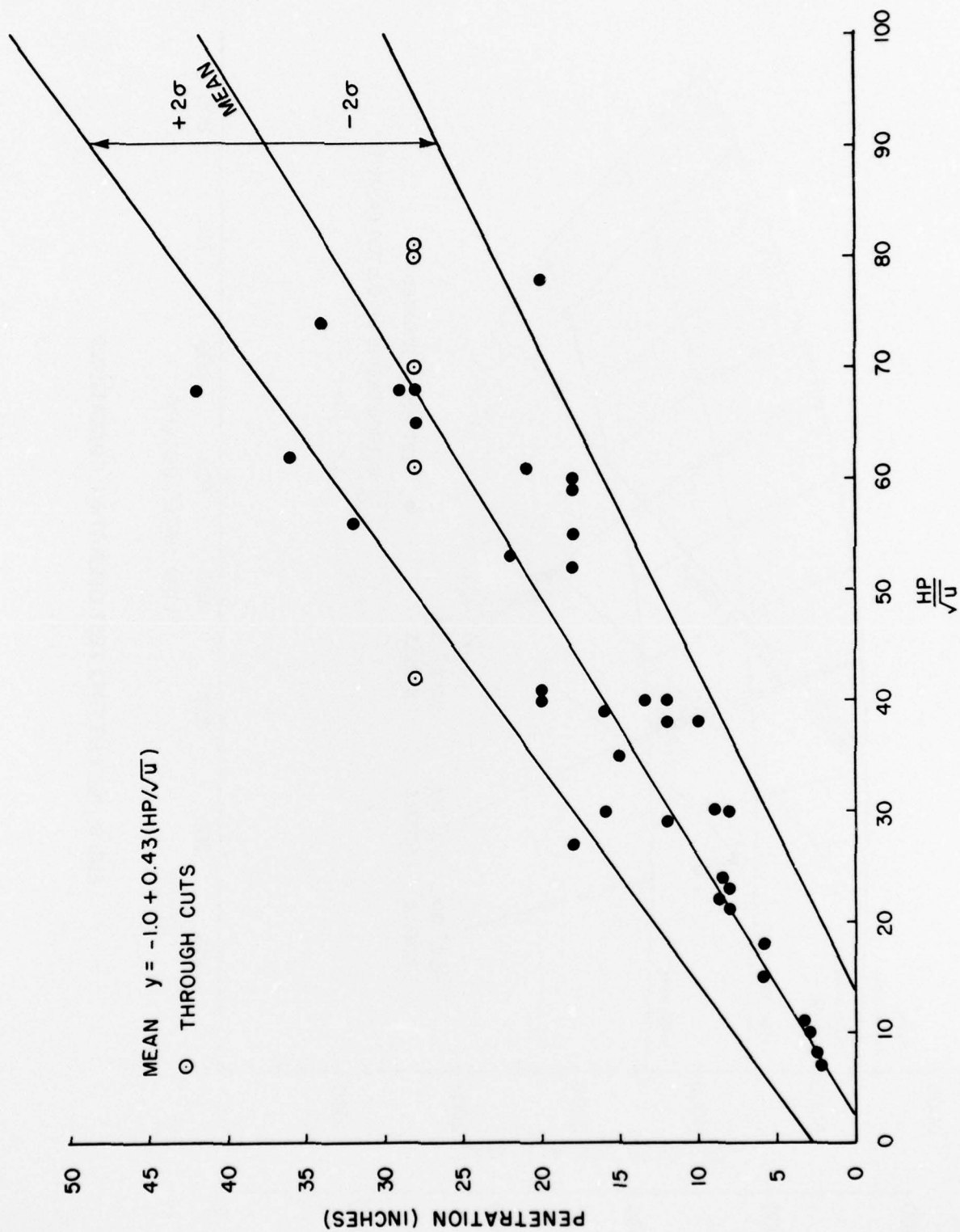


FIG. 10: ICE CUTTING WITH WATER JETS

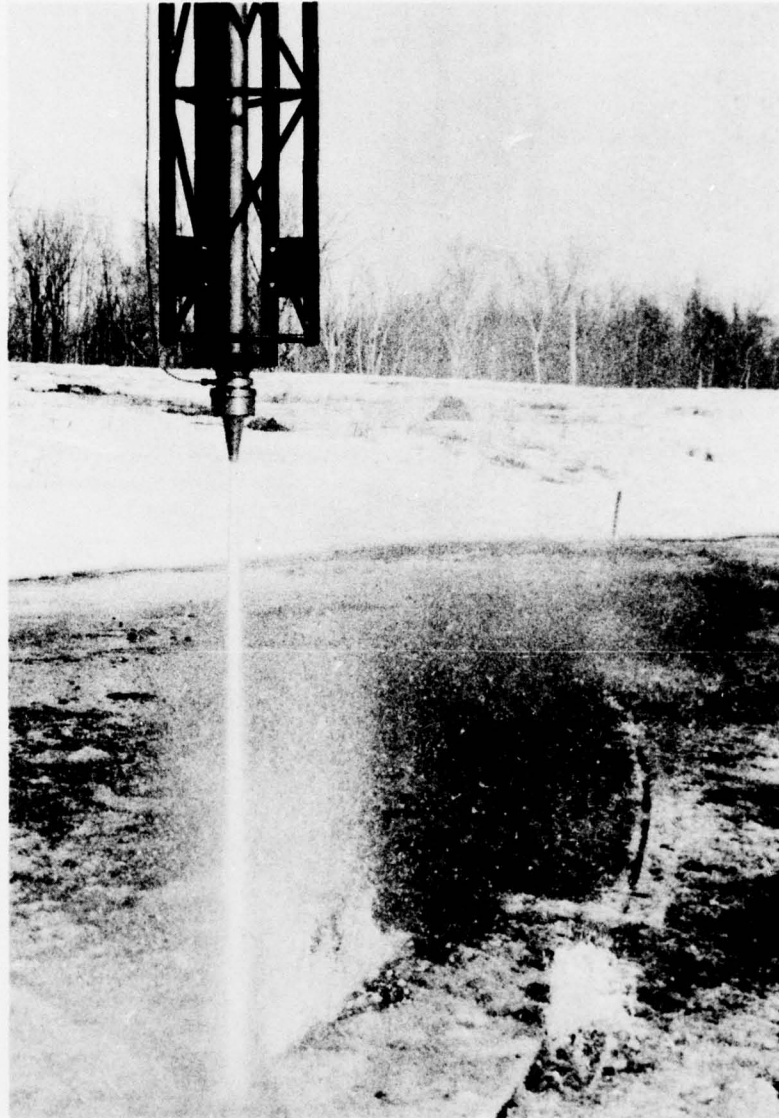


FIG. 11: WATER JET ESCAPING BETWEEN DELAMINATED ICE LAYERS



FIG. 12: ICE CUTTING DURING TEST NO. 9

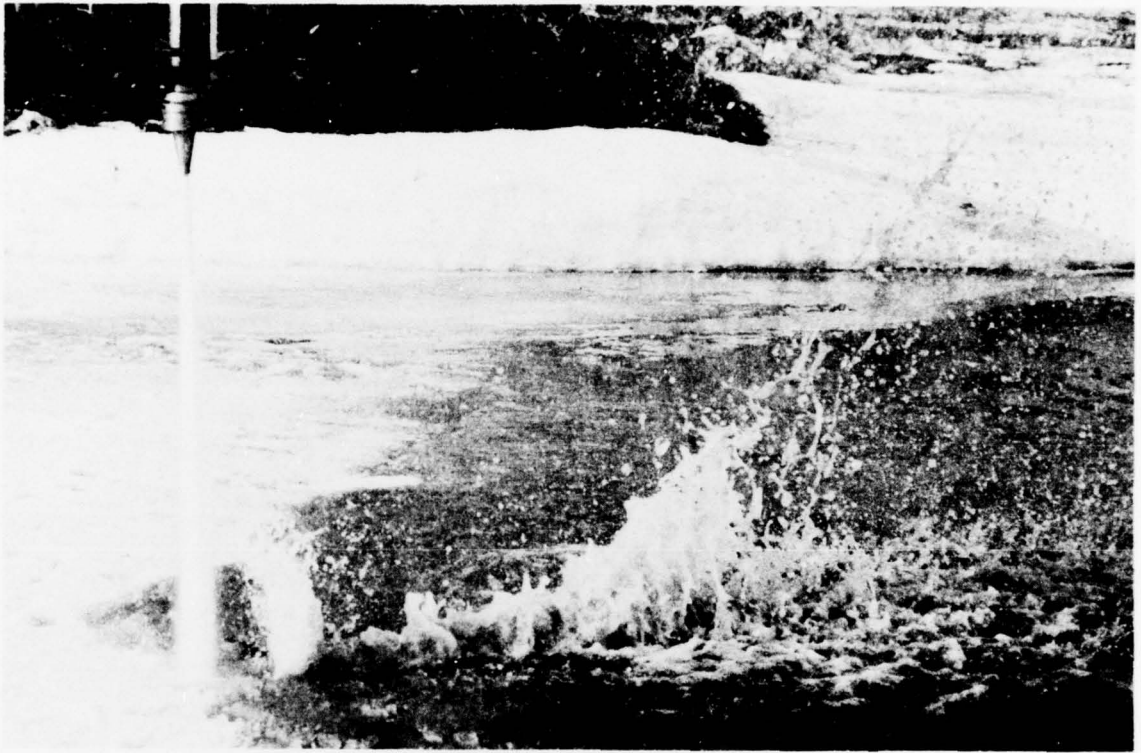


FIG. 13: ICE CUTTING DURING TEST NO. 13





FIG. 14: HIGH SPEED TRAVERSE OF ICE CUTTING TEST NO. 14



FIG. 15: CUT MADE DURING TEST NO. 3

## APPENDIX

### 1.0 MAIN PUMP

Make:	Bingham Pump Company
Size and Type:	4" X 4" X 10" MSB
No. Stages:	8
Rotation:	Clockwise (looking at coupling end)
Discharge:	4" dia. with 900 lb. ASA flange
Suction:	4" dia. with 300 lb. ASA flange
Bearings:	Ball bearings for both radial and thrust loads, self circulating oil lubrication, water cooled
Seals:	8 ring packings in each box with lantern rings for water lubrication, water cooled
Rating:	At 3,570 rpm, 600 US gpm @ 3,000 ft. head (1,350 psig) with suction pressure of 50 psig pumping water with S.G. = 1.0 at normal temperatures

### 2.0 DIESEL ENGINE

Make:	Caterpillar
Model:	D346 Watercooled
Type:	4 stroke cycle
Aspiration:	Turbo-charged and aftercooled
Cylinders:	V-8
Bore & Stroke:	5.4 in. X 6.5 in.
Displacement:	1,191 cu. in.
Rotation:	Counter-clockwise (looking at flywheel end)
Starting:	24 volt heavy duty electric starter with glow plugs for cold weather starting assistance
Batteries:	Two 12 volt heavy duty, connected in series
Battery Charging:	Heavy duty alternator
Fuel:	No. 2 light diesel fuel
Fuel Tank:	250 I gal. located below main pump

Cooling:	Two closed circuit coolant systems, one for the engine jacket and one for the aftercoolers discharge heat into the main water system through heat exchangers
Silencer:	Residential grade mounted on the roof of the container
Safety Shut-offs:	Mechanical, protect engine against over-temperature, over-speed and low engine oil pressure
Instruments:	Engine rpm tachometer Fuel pressure gauge Engine oil pressure gauge Jacket coolant temperature gauge

### 3.0 SPEED INCREASER

Make:	Falk Corporation
Size:	13.166" × 16-3/4"
Gear:	112 teeth
Pinion:	51 teeth
Type:	Herringbone
Lubrication:	Oil circulation pump driven from speed increaser

### 4.0 CLUTCH COUPLING, ENGINE — SPEED INCREASER

Make:	BLM Automatic Clutch Ltd.
Type:	PMH140-192 centrifugal clutch
Mounting:	On front end of engine

### 5.0 COUPLING, SPEED INCREASER — MAIN PUMP

Make:	Sier-Bath
Type:	Flexible gear coupling
Size:	C-3

### 6.0 BASE FRAME

Main Rails:	12" × 8" × 5/16" hollow structural steel tubing
Cross Rails:	8" × 6" × 1/4" hollow structural steel tubing
Construction:	Welded



## 7.0 CONTAINER

Make: Steadman Containers Limited  
Size: 20' X 8' X 8'  
Type: ISO, Group IC heavy duty  
Specification: S-1226  
Construction: Aluminum and steel

## 8.0 FEED PUMP

Make: Gorman-Rupp of Canada Ltd.  
Type: Self priming centrifugal  
Model: O4C3-B  
Size: 4" X 4"  
Bearings: Ball bearings  
Seal: Mechanical self-lubricated

## 9.0 SPARK-IGNITION ENGINE

Make: Teledyne Wisconsin Motor  
Model: VH4D air cooled  
Type: 4 stroke cycle  
Cylinders: V-4  
Bore & Stroke: 3-1/4 in. X 3-1/4 in.  
Displacement: 108 cu. in.  
Starting: 12 volt electric starter with automatic choke  
Battery: 12 volt  
Battery Charging: Alternator  
Fuel: Regular grade gasoline, gravity fed  
Fuel Tank: 5 I gal. engine mounted  
Power Take-off Clutch: Integral with engine, manually engaged

## 10.0 COUPLING, ENGINE --- FEED PUMP

Make: Falk Corporation  
Type: Standard Type F Steelflex  
Size: 9F

NRC, DME MD-54

National Research Council Canada. Division of Mechanical Engineering.

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From current and previous ice cutting tests it has been established that significant cuts in ice can be made over a wide range of conditions. At moderate pressures, that is less than 2,000 psig, and low traverse speeds, it has been possible to cut through ice 28 inches thick. Correlation with previous test results by regression analysis has been made.

UNCLASSIFIED

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